

Excavating a Buried Higgs

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Yale

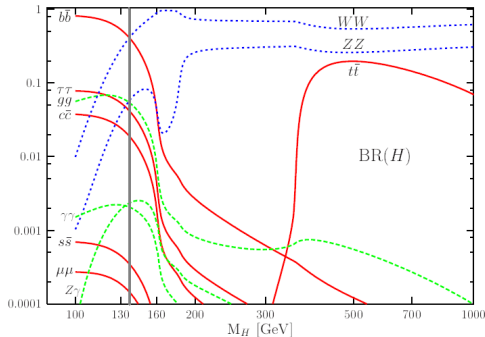
[arXiv:1006.1650](https://arxiv.org/abs/1006.1650)

with A. Falkowski, D. Krohn, A. Thallapillil, and L.-T. Wang

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A light Higgs at the LHC

- A light Standard Model Higgs is a challenging signal at the LHC:

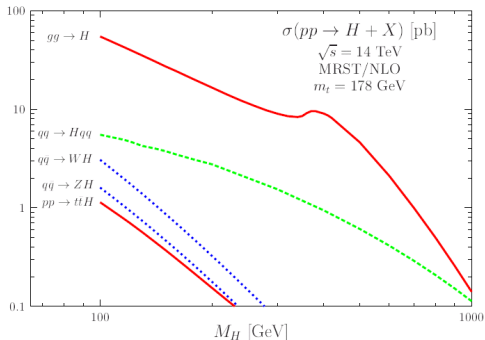


SM BRs as a function of m_h

$m_h < 135$ GeV : $h \rightarrow b\bar{b}$

- QCD backgrounds for a dominant hadronic decay mode are immense.

Strategies for a light Higgs



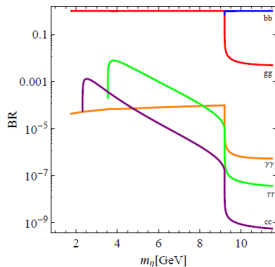
- $gg \rightarrow h$, $qq \rightarrow hqq$: a hadronic h leads to difficult all-hadronic final states
- $V + h$, $t\bar{t} + h$: better, but backgrounds $V + \text{jets}$, $t\bar{t} + \text{jets}$ are still very large
- **jet substructure**: tools capable of digging a hadronic h out of the QCD radiation

A light SM-like Higgs is *narrow*

- Small matter Yukawas: $\Gamma_h(m_h = 120 \text{ GeV}) = 3.7 \text{ MeV}$
- \Rightarrow New physics coupling to H can easily change branching fractions by $\mathcal{O}(1)$, with minimal changes to EWSB
- For example: $\Delta\mathcal{L} = \lambda_s |H|^2 s^2$
 - $\Gamma(h \rightarrow ss) \sim m_h \frac{\lambda_s^2}{\lambda_h^2}$; $\Gamma(h \rightarrow b\bar{b}) \sim m_h y_b^2$
 - large range of parameter space: $BR(h \rightarrow ss) > BR(h \rightarrow b\bar{b})$
 - final state then depends on $BR(s \rightarrow X)$'s
- Theoretically appealing: reduce tuning in Higgs potential, utilize portal to hidden sectors
- Relatively **easy to achieve**: should be prepared to cover parameter space at LHC

Buried Higgs

- A reference model explicitly realizing interesting scenarios for both LEP and LHC
- “Double protection”: a SUSY little Higgs Bellazzini, Csáki, Falkowski, Weiler, '09
- H_d, H_u, a : PNCBs with loop-generated masses
- a is naturally light (few GeV) and couples to SM fermions through mixing with heavy vector-like partners of third-generation fermions
- Dominant decay $a \rightarrow gg$
- Limits and discovery:
 - current limits from LEP:
 $m_h \gtrsim 86 \text{ GeV}$
 - what about the LHC?



Buried Higgs at the LHC

- Search strategies for $h \rightarrow aa \rightarrow 4X$, $2X2Y$ depend critically on
 - m_a : separation of decay products
 - $BR(a \rightarrow 2X)$: especially to non-hadronic ($\gamma\gamma$, $\mu\mu$, $\tau\tau$) or taggable (bb , $\tau\tau$) final states
- Discovery is easiest when:
 - isolated taggable decay products in final state (e.g., $4b$)
Cheung, Song, Yan, '07; Carena et al., '07
 - or BR s to rare clean decay modes are not too suppressed
Dobrescu, Landsberg, Matchev, '00; Chang, Fox, Weiner, '06; Lisanti, Wacker '08
- Light a and suppressed BR s to non-hadronic final states put a buried Higgs out of reach with these approaches
- To take full advantage of LHC discovery potential we must develop discovery techniques for the dominant all-hadronic decay mode $h \rightarrow aa \rightarrow 4g$

Jet substructure and the Higgs

- Jet substructure can rescue the utility of hadronic Higgs decay modes Butterworth, Davison, Rubin, Salam '08

- In the standard model: $pp \rightarrow V + (h \rightarrow b\bar{b})$

- 1 Go to **boosted regime**: improve S/B
- 2 Look for **substructure** to differentiate collimated H decays from QCD radiation
- 3 **Groom** jets: minimize contribution from unrelated soft radiation to improve mass resolution
- 4 Utilize **b -tags** to further suppress QCD background

Jet substructure and the Higgs

- Jet substructure can rescue the utility of hadronic Higgs decay modes Butterworth, Davison, Rubin, Salam '08
- $pp \rightarrow V + (h \rightarrow b\bar{b})$ as a discovery channel:
 - ① Go to **boosted regime**: improve S/B
 - Different scaling of signal and background in boosted regime:
 - signal: $m_{b\bar{b}}$ fixed, $\Delta R_{b\bar{b}} \sim m_{b\bar{b}}/p_{Tb\bar{b}}$
 - background: for a given ΔR_{jj} , $m_{jj} \propto p_{Tjj} \Delta R_{jj}$
 - large p_T : signal has large $m_{b\bar{b}}$ and small $\Delta R_{b\bar{b}}$
background, large $m_{b\bar{b}}$ and large $\Delta R_{b\bar{b}}$
 - in boosted regime, h collected in single fat jet ($R \simeq 1-1.5$)

Jet substructure and the Higgs

- Jet substructure can rescue the utility of hadronic Higgs decay modes Butterworth, Davison, Rubin, Salam '08
- $pp \rightarrow V + (h \rightarrow b\bar{b})$ as a discovery channel:
 - ② Look for **substructure** to differentiate collimated H decays from QCD radiation
 - Resolve fat jet on finer angular scales looking for a hard splitting characteristic of a boosted hard decay:
 - Find hard subjets inside fatjet at a smaller angular scale R_{eff}
 - Can choose R_{eff} event by event using a sequential declustering procedure Butterworth, Davison, Rubin, Salam '08: determine R_{eff} from the first sufficiently interesting splitting in the sequence
 - We will use a fixed angular scale for subjets

Jet substructure and the Higgs

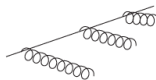
- Jet substructure can rescue the utility of hadronic Higgs decay modes Butterworth, Davison, Rubin, Salam '08
- $pp \rightarrow V + (h \rightarrow b\bar{b})$ as a discovery channel:
 - ③ **Groom** jets: minimize contribution from unrelated soft radiation to improve mass resolution
- LHC is a busy hadronic environment. Jets will typically contain contributions from multiple different sources:
 - wide-angle emission from other partons from primary scatter, underlying event, pile-up
- Soft contamination distorts jet properties and in particular invariant mass
- \Rightarrow Require an algorithm to remove contributions of unrelated soft radiation, especially for large jets
 - **filtering** Butterworth, Davison, Rubin, Salam '08
 - **pruning** Ellis, Vermilion, Walsh '09
 - **trimming** Krohn, Thaler, Wang '09 \leftarrow we will use this one

Jet substructure and the Higgs

- Jet substructure can rescue the utility of hadronic Higgs decay modes Butterworth, Davison, Rubin, Salam '08
- $pp \rightarrow V + (h \rightarrow b\bar{b})$ as a discovery channel:
 - ④ Utilize b -tags to further suppress QCD background
 - SM analysis requires 2 b -tags

Boosted BSM $h \rightarrow 4g$

- $h \rightarrow aa \rightarrow 4g$ looks like $h \rightarrow j_a j_a$ at LHC energies: do not resolve $a \rightarrow gg$ splitting
- This is a similar topology to SM. But **no b tags**. Are we dead?
- ① A boosted a does not look like a generic QCD jet: new jet variables to distinguish j_a from QCD radiation
 - less radiation



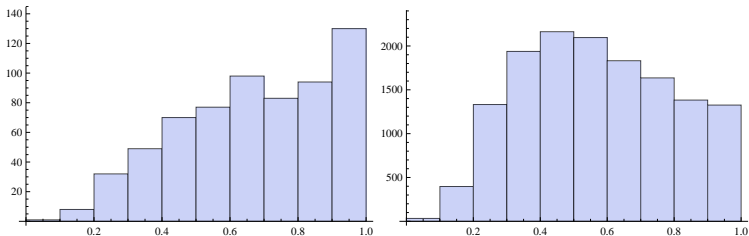
- presence of *small* mass scale $m_a \ll p_{Ta}$
- ② For non-SM Higgs, $t\bar{t}h$ production channel is **more useful**:
- SM: in addition to large $t\bar{t} + jj$ background, severe combinatoric background: $t\bar{t} \rightarrow b\bar{b}WW$
 - non-SM: with leptonic tops, can cleanly separate top and Higgs decay products

Distinguishing a Higgs jet from a QCD jet



- As in SM, start with jet clustered on large scale to select initial Higgs candidate
- resolve on finer angular scales to distinguish properties
- look for evidence of hard splitting to 2 particles with identical mass:
 - require 2 subjets with $p_{Ti} > f_i p_{T,tot}$
 - “mass democracy”: $\alpha \equiv \min \left[\frac{m_{j1}}{m_{j2}}, \frac{m_{j2}}{m_{j1}} \right] > \alpha_{cut}$

Distinguishing a Higgs jet from a QCD jet



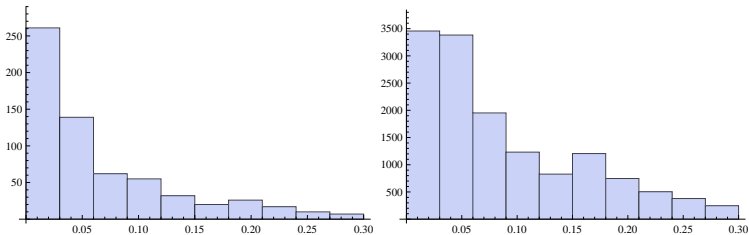
- signal and background distributions of α in $t\bar{t} + h$ after requiring $p_T > 125$ GeV

Distinguishing a Higgs jet from a QCD jet



- Only final stage of signal cascade decay involves colour sources: low mass and small angle
- \Rightarrow expect minimal radiation between subjets see also: Galliccio, Schwartz, '10
- *colour flow*: $\beta = \frac{p_{Tj3}}{p_{Tj}} < \beta_{cut}$
 - definition with single jet: reduce sensitivity to pileup
- sensitivity depends on p_T threshold for soft jets

Distinguishing a Higgs jet from a QCD jet



- signal and background distributions of β in $t\bar{t} + h$ after requiring $p_T > 125 \text{ GeV}$; $p_{T,soft} > 1 \text{ GeV}$

Distinguishing a Higgs jet from a QCD jet



- Select moderately or highly boosted Higgs to control backgrounds (physics or combinatorics)
- \Rightarrow QCD jets passing cuts have likewise hard p_T spectrum
- QCD: $\langle m^2 \rangle = \frac{\alpha_s C_F}{\pi} p_T^2 R^2 + \dots$
- require $(m_{j1} + m_{j2})/2 < m_{cut}$

Distinguishing a Higgs jet from a QCD jet



- Some further possibilities:
 - **Track counting**: low-scale gluon-initiated jets are comparatively track-sparse, and track counting may be an efficient discriminant
 - **Resolving $a \rightarrow gg$** : If it is possible to resolve perturbative splitting $a \rightarrow gg$, this additional substructure variable can help distinguish between the collimated a and the more hierarchical background
- Chen, Nojiri, Sreethawong '10
- While promising, will not include in results

Results

A few notes about event generation:

- Signal and background processes are generated with MadGraph/MadEvent for $t\bar{t}h$ and in Pythia for $W + h$ and showered with Pythia (k_T -ordered); clustering is done using FastJet with some additional clustering done in Mathematica
- Include pile-up and underlying event
- For $t\bar{t}h$: main backgrounds $V + j$, $t\bar{t} + jj$ are matched using MadGraph's native k_T -MLM procedure
- Results robust under changing model of parton shower (Pythia Q^2 -ordered) and choice of matching scheme (shower- k_T)
- Also consider subdominant backgrounds (for $t\bar{t}h$: $t\bar{t}Z$, $Z + jj$)

Results: $t\bar{t}h$

A few notes about event generation:

- 3 signal samples: $m_h = 80$ GeV, 100 GeV, 120 GeV,
 - $m_a = 8$ GeV
- develop two sets of cuts, for $m_h = 120$ GeV and $m_h \leq 100$ GeV
- Assume SM production cross sections and 100% BR to $4g$ final state

Cut flow for $t\bar{t} + h$: preselection

	σ_{sig} (fb)	σ_{bkgd} (fb)	S/B	S/\sqrt{B} at 100 fb $^{-1}$
preselection	8.1	6700	1.2×10^{-3}	1.0

- Select for top decay products: 2 b , 2 ℓ , MET; leptonic Z-window veto; jets found with anti- k_T , $R = 0.4$
- Model b tagging efficiency with simple 0.6 flat tagging rate
- cluster jets with $p_T > 10$ GeV with $R = 1.5$;
- trim fat jets: drop $R = 0.4$ subjets with $p_T < 0.15 p_{T,tot}$
- Higgs candidate is the hardest fat jet in the event.

Cut flow for $t\bar{t} + h$: kinematics and substructure

	σ_{sig} (fb)	σ_{bkgd} (fb)	S/B
preselection	8.1	6700	1.2×10^{-3}
kinematics	1.7	220	7.8×10^{-3}
mass democracy	0.96	76	1.2×10^{-2}

- look at **hard** fat jets: $p_T > 125$ GeV,
- which contain hard **subjets**: $j \supset j_1, j_2$ with $p_T > 40$ GeV
- mass democracy cut on hardest subjets: $\alpha(j_1, j_2) > 0.70$

Cut flow for $t\bar{t} + h$: colour cuts

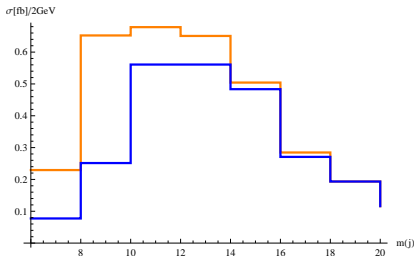
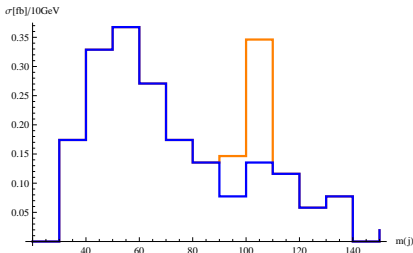
	σ_{sig} (fb)	σ_{bkgd} (fb)	S/B
subjet kinematics	0.96	76	1.2×10^{-2}
$\beta < 0.03$	0.43	17	2.6×10^{-2}

- **Colour flow**: consider set of $R = 0.4$ subjets within $R = 1.5$ of jet centroid
 - consider two different thresholds for soft jets: 5 GeV and 1 GeV
 - best results (shown here): p_T thresholds at 1 GeV
 - good results for β cut at $p_T > 5$ GeV
- require $\beta(j_3) < 0.03$

Cut flow for $t\bar{t}h$: mass window cuts

	σ_{sig} (fb)	σ_{bkgd} (fb)	S/B	S/\sqrt{B} (100 fb $^{-1}$)
colour flow	0.43	17	2.6×10^{-2}	1.1
subjet mass	0.28	1.9	0.14	2.0
Higgs window	0.28	0.21	1.3	6.1

- jet mass: require $|m_j - m_h| < 10$ GeV
- subjet mass: require $(m_1 + m_2)/2 < 10$ GeV



Background in blue, signal plus background in orange

Results: $W + h$

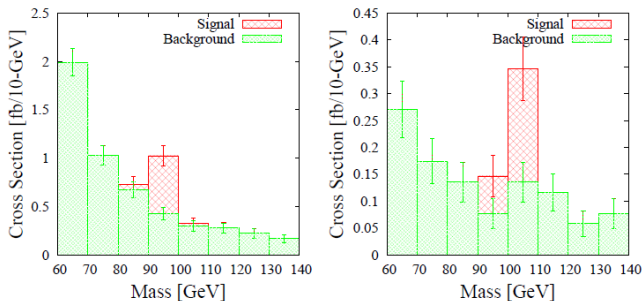
- Similar cuts for $W + h$ channel: parameters adjusted for different kinematics of final state
- **Preselection**: cluster event on large scale, $R = 1.0$ for $m_h = 100$ GeV, and ask for
 - a hard jet: $p_T > 200$ GeV
 - a lepton from the W
- **Resolve subjects** on the finer scale $R = 0.3$.
- Impose **subject cuts** on the 2 hardest subjects:
 - mass democracy $\alpha < 0.7$
 - colour flow $\beta < 0.005$
 - subject mass cut $\bar{m} < 10$ GeV
 - For mass cuts, trim subjects using $f = 0.03$

Results: $W + h$

	σ_{sig} (fb)	σ_{bg} (fb)	S/B	S/\sqrt{B}
$p_T(j) > 200$ GeV	16	30000	5.2×10^{-3}	0.9
subjct mass	12	19000	6.2×10^{-3}	0.9
Higgs window	7.1	400	1.8×10^{-2}	3.6
$\alpha > 0.7$	4.1	140	3.0×10^{-2}	3.5
$\beta < 0.005, p_T^{\min} = 1$ GeV	0.67	0.74	0.90	7.8
$\beta < 0.005, p_T^{\min} = 5$ GeV	2.9	2.6	0.11	5.7

results are again for 100 fb^{-1}

Combining channels



Reconstructed h mass in the $W + \text{jets}$ (left) and $t\bar{t} + \text{jets}$ channels (right). Error bars show statistical errors.

Combining channels

- Results for Higgses above and below 114 GeV in both channels:

		$m_h = 80 \text{ GeV}$	$m_h = 100 \text{ GeV}$	$m_h = 120 \text{ GeV}$
$W + h$	S/\sqrt{B}	6.6 (4.8)	7.8 (5.7)	7.0 (6.9)
	S/B	0.34 (0.067)	0.90 (0.11)	0.80 (0.24)
$t\bar{t} + h$	S/\sqrt{B}	6.1 (5.9)	6.1 (5.7)	7.1 (7.1)
	S/B	1.1 (0.97)	1.3 (1.1)	2.5 (2.5)

- Numbers outside (inside) parentheses are for soft radiation thresholds 1 (5) GeV
- Without colour flow cut: 3σ
- Cuts are optimized for $m_h \leq 100 \text{ GeV}$ and $m_h = 120 \text{ GeV}$ separately.

Conclusions

- A light Higgs, even if not below LEP limit, can easily decay to a complicated multi-particle final state which can be challenging at the LHC.
- A light Higgs with dominant non-Standard Model decay mode $h \rightarrow 4g$ can be discovered at the LHC
- Two useful production channels: $V + h$ and $t\bar{t} + h$
 - increased significance
 - measurement of multiple couplings
- $t\bar{t}h$ relatively more useful for BSM Higgses than SM Higgses: combinatoric background ameliorated
- Color flow observables have promise to extend LHC BSM sensitivity, both in other Higgs searches and beyond